

## HADRON-HADRON INTERACTIONS \*

K. Holinde

*Institut für Kernphysik (Theorie), Forschungszentrum Jülich GmbH,  
D-52425 Jülich, Germany*

## ABSTRACT

The present status of the chiral approach to the  $NN$  interaction as proposed by Weinberg is discussed. The important role of correlation effects and explicit vector meson ( $\rho$ ,  $\omega$ ) exchange in the dynamics of baryon-baryon interactions is demonstrated. As an example, the inclusion of the exchange of a correlated pair of  $\pi$  and  $\rho$  meson between two nucleons appears to be mandatory in order to resolve a long-standing puzzle concerning the formfactor at the pion-nucleon-nucleon vertex.

**1. Introduction**

Quantum chromodynamics (QCD) is the underlying theory of strong interactions, with quarks and gluons as fundamental degrees of freedom. However, in the non-perturbative region of low and medium energy physics, mesons and baryons definitely keep their importance as efficient, collective degrees of freedom for a wide range of nuclear phenomena. There is a widespread view that a successful effective field theory in terms of hadronic degrees of freedom should have the same symmetries as QCD. Chiral symmetry, in the limit of vanishing quark masses, is an exact QCD symmetry; chiral perturbation theory<sup>1</sup> is an effective field theory in terms of the light pseudoscalar mesons ( $\pi, K, \eta$ ), the Goldstone bosons of spontaneously broken chiral symmetry. It is important to realize that such an effective field theory is mathematically equivalent to QCD. At sufficiently low energies, smaller than the QCD mass scale of about 1 GeV, it leads to a systematic expansion of effective Lagrangians and scattering amplitudes in powers of momenta and quark masses (the latter arise from the symmetry breaking terms).

Of course, the effectiveness (as a fastly converging scheme) of chiral perturbation theory is by definition restricted to quite low energies. Moreover, a perturbational method can only work if the interactions are weak, which is the case for reactions involving the Goldstone bosons as external particles. Given these constraints, chiral perturbation theory is remarkably successful; for a review, see e.g. the recent article by Meissner<sup>2</sup>.

---

\*Invited talk presented at the Conference on Physics with GeV-Particle Beams, Jülich, Germany, August 22-25, 1994.

On the other hand, for baryon-baryon and baryon-antibaryon interactions strong correlation effects appear already at threshold; it is hard to get such effects from an expansion which, for practical reasons, has to be limited to low orders. Furthermore, higher-mass mesons, especially vector mesons  $\rho$  and  $\omega$ , play an important role. In my opinion, a successful description requires to treat both dynamical mechanisms explicitly, as will be discussed below.

## 2. Chiral Dynamics in the nucleon-nucleon system.

Let me start by looking at present chiral treatments of the nucleon-nucleon ( $NN$ ) system. Recently, quite a lot of papers have appeared dealing with this issue <sup>3-6</sup>. Whereas Refs. <sup>3-5</sup> concentrated on the chiral structure of a specific contribution to the  $NN$  interaction, namely  $2\pi$ -exchange, Ref. <sup>6</sup> presented a “complete”  $NN$  potential strictly obeying chiral symmetry. It is based on the most general effective chiral Lagrangian involving low momentum pions, nonrelativistic nucleons and  $\Delta$ -isobars, and is considered up to third order  $((Q/M)^3$ , with  $Q$  a typical external momentum and  $M$  the QCD mass scale) in the chiral expansion, thus containing tree as well as one-loop diagrams.

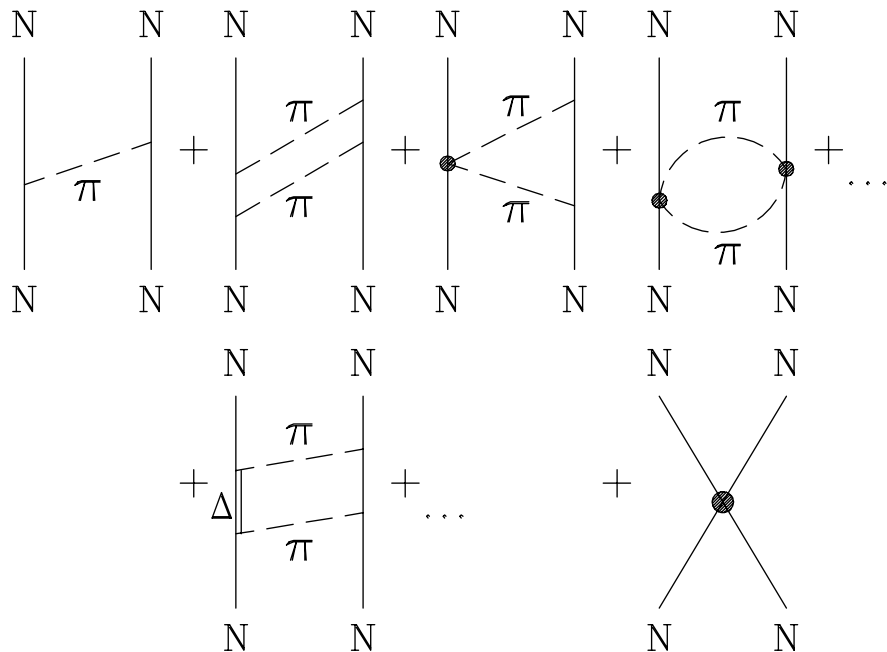


Figure 1: Diagrams included in the chiral approach of Ref. <sup>6</sup>.

In diagrammatic terms, the resulting  $NN$  potential has the structure shown in Fig. 1. It consists of one-pion-exchange (OPE) and  $2\pi$ -exchange terms with  $N$  and  $\Delta$  intermediate states. There are additional  $2\pi$ -exchange processes in the chiral approach (Ref. <sup>6</sup>) involving the  $N\bar{N}\pi\pi$  vertex (see Fig. 1), whose presence is dictated by chiral symmetry. However, due to partial cancellations (Refs. <sup>5, 4</sup>) they are

Table 1: Deuteron properties predicted by the chiral model of Ref. <sup>6</sup>, the Bonn  $NN$  potential (Ref. <sup>7</sup>), and the Bonn potential with a soft  $\pi NN$  form factor ( $\Lambda_{\pi NN} = 1 GeV$ ) plus correlated  $\pi\rho$  exchange (Ref. <sup>8</sup>) as discussed in Section 5. For the experimental values, see Refs. <sup>7, 9</sup>.

	experiment	chiral model (Ref. <sup>6</sup> )	Bonn (Ref. <sup>7</sup> )	modified Bonn
Binding energy (MeV)	2.2245754	2.18	2.2247	2.2246
Quadrupole moment ( $fm^2$ )	$0.2859 \pm 0.0003$	0.231	0.2807	0.2791
asymptotic D/S ratio	$0.0256 \pm 0.0004$ ( $0.0271 \pm 0.0008$ )	0.0239	0.0267	0.0266

actually quite small, much smaller e.g. than “ $\sigma$ ”- exchange representing correlated  $2\pi$ -exchange in the scalar-isoscalar channel, which provides the main part (about  $2/3$ , see Ref. <sup>7</sup>) of the  $NN$  intermediate range attraction. The chiral approach absorbs this contribution together with other important pieces involving vector ( $\rho, \omega$ ) mesons into the contact terms, i.e. terms of zero range (last diagram of Fig. 1). In order to solve the corresponding Schroedinger equation a Gaussian cutoff function,  $exp(-Q^2/L^2)$ , with  $L = 3.9 fm^{-1}$ , has been used. Results for some low ( $S$  and  $P$ )  $NN$  partial wave phase shifts are shown in Fig. 2 (taken from Ref. <sup>6</sup>), in comparison to those obtained from the (full) Bonn potential<sup>7</sup>. In addition, table 1 shows some deuteron parameters.

In this first confrontation of a chiral  $NN$  potential à la Weinberg to the very precise  $NN$  data rough agreement is reached in the low-energy domain. Note that this model has 26 parameters available (mainly the coefficients in the contact terms) compared to about 10 meson-baryon coupling constants and formfactor parameters in the Bonn potential. A combined look at the  $\varepsilon_1$ -parameter and deuteron parameters ( $Q$ ,  $D/S$ ) is instructive since both measure the size of the  $NN$  tensor force. Obviously, in the present chiral model, the energy dependence of this piece is not realistic since the deuteron values are too low whereas the  $\varepsilon_1$ -values grow too fast with increasing energy. There are two possible sources for this discrepancy: First, the chiral expansion introduces a polynomial momentum dependence, with adjustable parameters, at the  $\pi NN$  vertex; it should be checked by the authors of Ref. <sup>6</sup> whether their parametrization chosen is in reasonable agreement with the known monopole structure of the  $\pi NN$  formfactor, see Section 4. Furthermore,  $\rho$ -exchange provides an important contribution to the tensor force (see Section 3) reaching out well into intermediate  $NN$  distances of  $1 - 2 fm$ . It is highly questionable whether this piece (as well as “ $\sigma$ ” and  $\omega$  exchange) can be sufficiently represented by zero-range contact terms.

In my opinion, in present chiral approaches to the  $NN$  system, the price you pay (having to treat important contributions in a very rough way) is too high for

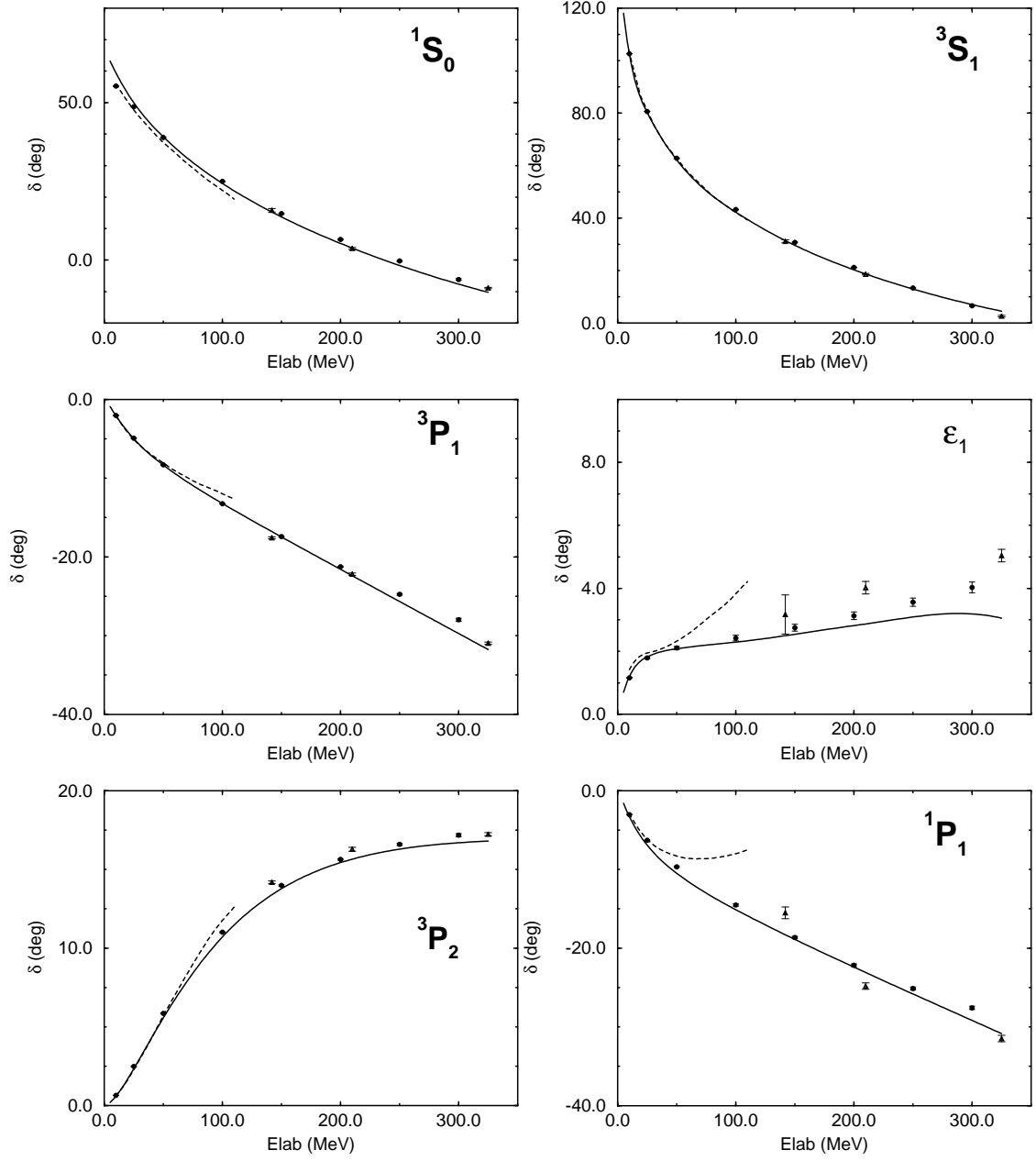


Figure 2:  $NN$  phase shifts, in selected partial waves, as a function of the nucleon lab. energy. The solid lines give the predictions derived from the Bonn potential (Ref. <sup>7</sup>) whereas the dashed lines, taken from Ref. <sup>6</sup>, originate from the chiral approach. The experimental error bars are taken from Refs. <sup>10, 11</sup>

what you get (a strict chirally symmetric  $V_{NN}$  derived from a systematic expansion).

### 3. Structure of $\pi$ and $\rho$ exchange in the $NN$ system

It is well known that the physics of “ $\sigma$ ” and  $\rho$  exchange, so important in the  $NN$  system, is mainly built up by correlated  $2\pi$ -exchange. (For a recent dynamical model suitable for the discussion of medium modifications, see the paper by Kim et al.<sup>12</sup>.) Therefore, in principle, the chiral approach can take such effects, at least to some extent, into account by going to still higher orders in the chiral expansion, at the expense of getting additional open parameters.

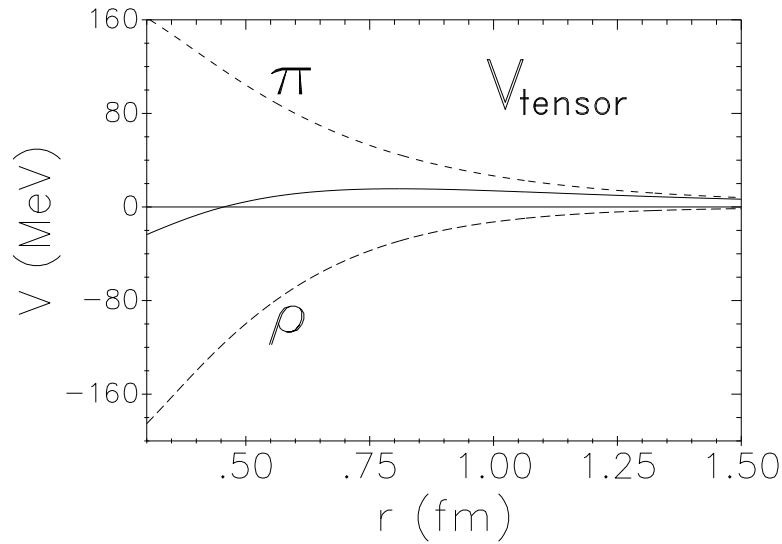


Figure 3:  $NN$  tensor force  $V_T(r)$  as function of the two-nucleon distance  $r$ , due to  $\pi$  and  $\rho$  exchange. The solid line denotes the sum of both contributions. The parameter values are taken from OBEPR (Ref. <sup>7</sup>).

The importance of  $\rho$ -exchange for the dynamics of the  $NN$  system derives from the following fact: It provides a sizable tensor force, which has opposite sign to the tensor force generated by one-pion-exchange, see Fig. 3. Thus there is a strong cancellation, over a relatively broad range of energies and distances, between  $\pi$  and  $\rho$  exchange in the tensor channel. A similar cancellation occurs in the strange sector, between  $K$  and  $K^*$  exchange, e.g. in the hyperon-nucleon interaction. Therefore, in the  $NN$  (and in the baryon-baryon system in general) it is strongly suggested to always group  $\pi$  and  $\rho$  (as well as  $K$  and  $K^*$ ) together in order to reach sufficient convergence in the expansion of the irreducible kernel (potential). To single out  $\pi$ -exchange as done in the chiral approach might be more systematic from a formal point of view; on the other hand, by putting  $\rho$ -exchange into the contact terms, one essentially loses the strong convergence-generating mechanism at intermediate distances provided by  $\rho$ -exchange. Thus, from a physical standpoint, it appears mandatory to treat  $\pi$  and  $\rho$  exchange on an equal footing.

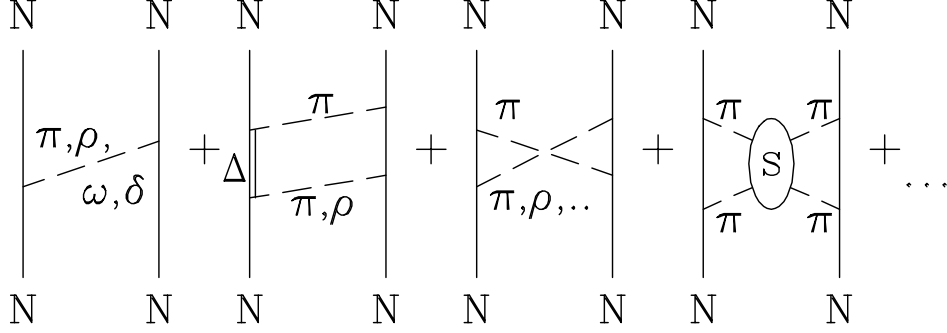


Figure 4: Diagrams included in the Bonn  $NN$  potential<sup>7</sup>.

In fact, this procedure has been an essential guideline when constructing the Bonn potential. Unfortunately (though for understandable reasons, see below) it was not followed to a sufficient degree: Whereas, in second-order diagrams (cp. Fig. 4)  $\pi\pi$  as well as  $\pi\rho$  exchange have been included for uncorrelated processes (with  $N$  and  $\Delta$  intermediate states) this has not been done for correlated processes: correlated  $2\pi$ -exchange processes have been included (in terms of sharp-mass  $\sigma'$  and  $\rho$  exchange) but correlated  $\pi\rho$  processes have been left out. The reason is quite simple: The evaluation of this missing piece is technically quite complicated, much more involved (due to the spin of the  $\rho$ ) compared to correlated  $2\pi$ -exchange. More importantly, a dynamical model for the interaction between a  $\pi$  and a  $\rho$  meson was not available.

At the time of the construction of the Bonn potential (about 10 years ago) the omission of this piece did not seem to be serious.  $NN$  scattering data in a broad energy range as well as the deuteron data are described quantitatively with the full Bonn model. So why care about a missing piece whose practical relevance was not at all obvious? Soon after the publication of the Bonn potential in 1987 it became however clear that omission of correlated  $\pi\rho$  exchange demanded a high price, and this has to do with the structure of the  $\pi NN$  vertex.

#### 4. The $\pi NN$ vertex

Basic ingredients of the Bonn meson exchange  $NN$  model<sup>7</sup> are the meson-baryon couplings or vertex functions visualized in Fig. 5. These vertex functions are the “elementary” building blocks of an effective and consistent meson exchange description based on QCD.

The analytic structure of these couplings is (essentially) determined by the quantum numbers of the particles involved at the vertex. The strength is parametrized by coupling constants  $g_{B'B\alpha}$ ; in addition, formfactors with cutoff masses  $\Lambda_{B'B\alpha}$  as additional parameters are included, which parametrize the effect of the hadron extension and therefore represent a truly physical concept. In general, the formfactor depends on all four-momenta of the particles involved at the vertex, i.e.  $F_{B'B\alpha} = F(q_{B'}^2, q_B^2, q_\alpha^2)$

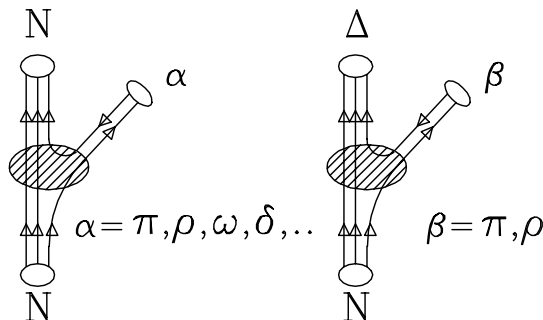


Figure 5: Baryon-baryon-meson couplings included in the Bonn  $NN$  potential (Ref. <sup>7</sup>).

and is normalized to 1 when all particles are on the mass shell.

While ultimately these formfactors have to be derived from QCD they are for the moment parametrized, usually in monopole form, keeping the dependence on the momentum of the exchanged particle only. With the additional suppression of the dependence on  $q_\alpha^0$ , the formfactors relevant in the  $NN$  system can then be written as

$$F_{B'B\alpha} = \frac{\Lambda_{B'B\alpha}^2 - m_\alpha^2}{\Lambda_{B'B\alpha}^2 + \vec{q}_\alpha^2} . \quad (1)$$

The cutoff masses  $\Lambda_{B'B\alpha}$  together with the coupling constants  $g_{B'B\alpha}$  represent the only parameters in the Bonn potential; they have been adjusted to the  $NN$  data. For the  $\pi NN$  cutoff mass,  $\Lambda_{NN\pi}$ , the resulting value turned out to be rather large ( $= 1.3\text{GeV}$ ) leading to a mild suppression of OPEP in the inner region ( $r \leq 1\text{fm}$ ) only, and thus to a hard formfactor. This is necessary in order to have sufficiently strong tensor force to reproduce the deuteron properties, especially the asymptotic  $D$ - to  $S$ -wave ratio and the quadrupole moment<sup>13</sup>.

However, there is a long-standing discrepancy between this rather large value required in present-day potential models and information from other sources; the latter consistently point to a much smaller value for  $\Lambda_{NN\pi}$  around  $0.8\text{GeV}$ <sup>14</sup>. In fact, a recent lattice calculation<sup>15</sup> of the  $\pi NN$  formfactor confirms this result, finding a monopole mass of  $(0.75 \pm 0.14)\text{GeV}$ . Such a soft formfactor leads to a strong suppression of the OPE tensor force already at intermediate distances, in apparent disagreement with the deuteron data. It is sometimes argued that a reduction (or even elimination) of  $\rho$  exchange in  $NN$  models would remedy the situation easily since the tensor force of  $\rho$  exchange has opposite sign compared to  $\pi$ -exchange. This can certainly be done if one looks at the deuteron channel only. However the sizable strength of  $\rho$  exchange is tightly constrained by informations from  $\pi N$  scattering via dispersion theory (see Ref. <sup>12</sup>) and in fact required by the precisely measured triplet  $P$ -wave  $NN$  phase shifts; it therefore cannot be arbitrarily changed.

Consequently we have to find mechanisms so far not included in meson exchange  $NN$  models which provide additional (short ranged) tensor force. Two years

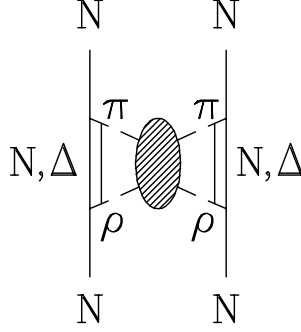


Figure 6: Model for the correlated  $\pi\rho$  exchange as evaluated in Ref. <sup>8</sup>.

ago it was pointed out by Ueda<sup>16</sup> that the contribution arising from the exchange of a correlated three-pion state between the nucleons, with the quantum numbers of a pion, should enhance the short-range tensor part of the  $NN$  interaction. Correlated  $\pi\rho$  exchange addressed in the foregoing chapter is a good part of it, and there is obviously no way around this contribution.

## 5. Correlated $\pi\rho$ exchange in the $NN$ system

The explicit evaluation of the diagram in figure 6 requires as input a realistic  $\pi\rho$   $T$ -matrix. In the absence of elastic  $\pi\rho$  scattering data (due to the fast decay of the  $\rho$  meson into 2 pions) we have to rely completely on a dynamical model.

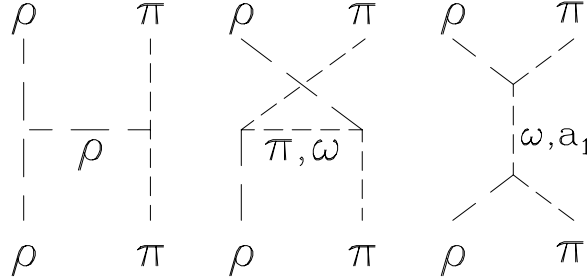


Figure 7: Driving terms for the  $\pi\rho$  interaction model of Refs. <sup>8</sup>, <sup>17</sup>.

We<sup>17</sup> have recently constructed a corresponding potential model, in complete analogy to the  $\pi\pi$  case (Ref. <sup>18</sup>), with driving terms shown in Fig. 7. Open parameters are adjusted mainly to empirical information in the  $a_1$ -channel (the  $a_1$  decaying into  $\pi$  and  $\rho$ ), namely the resonance parameters (pole position) of the  $a_1$ -particle<sup>19</sup> ( $m_{a_1} = 1.26\text{GeV}$ ,  $\Gamma_{a_1} = 0.4\text{GeV}$ ) obtained from  $\tau$ -meson decay, and the mass spectrum obtained from charge exchange production<sup>20</sup>,  $\pi p \rightarrow 3\pi n$ , see Fig. 8. Note that the shift of the maximum of the mass spectrum away from the true pole position is due to the sizable non-pole amplitude  $T_{np}$ , obtained by iterating  $V_{np}$  (the first two diagrams of Fig. 7.).



This non-pole contribution now acts in all other channels, e.g. in the pionic channel of interest here, with a definite strength distribution, which is characteristic of the underlying model.

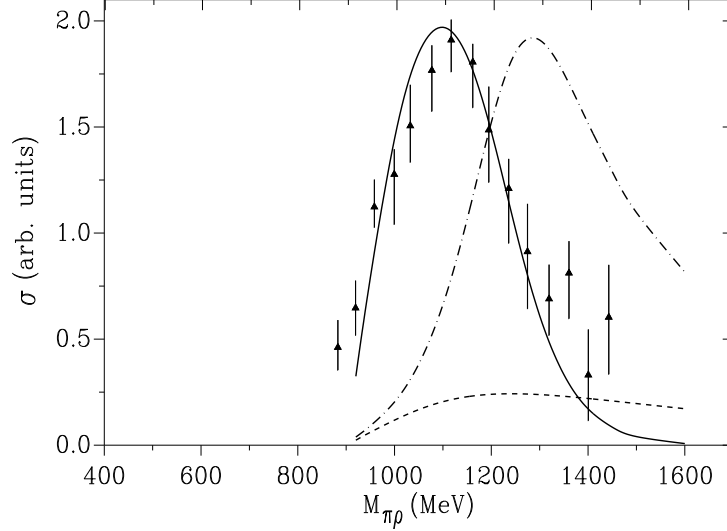


Figure 8: Mass spectrum in the  $a_1$  channel obtained from  $\pi p \rightarrow 3\pi n$  (Ref. <sup>20</sup>). The solid line shows the prediction of our full model whereas the dashed line denotes the result of the non-pole part of the  $T$ -matrix,  $T_{np}$ , only. The dash-dotted line provides the result of the pole part  $T_p$  only, with readjustment of the parameters to keep the same pole values

This  $\pi\rho$   $T$ -matrix is now inserted into the correlated  $\pi\rho$  exchange diagram of Fig. 6. The evaluation<sup>8</sup> proceeds via the same dispersion-theoretic treatment as used for the  $\pi\pi$  case in Ref. <sup>12</sup>. The result can be represented as integral over various spectral functions, the number of which depend on the considered channel. For the pionic channel we have one spectral function  $\rho^{(\pi)}$ :

$$V_{\pi\rho}^{(\pi)} \sim \int_{(m_\pi+m_\rho)^2}^{\infty} \frac{\rho^{(\pi)}(t')}{t' - t} dt'. \quad (2)$$

$\rho^{(\pi)}$  is shown in Fig. 9. Obviously the correlated part provides a sizable contribution, with a peak around  $1.1\text{GeV}$ , somewhat smaller than the mass ( $1.2\text{GeV}$ ) of the phenomenological  $\pi'$  introduced in some recent  $NN$  models to accommodate a soft  $\pi NN$  formfactor<sup>9</sup>.

Indeed, as shown in Fig. 10 and Table 1, the resulting interaction due to correlated  $\pi\rho$  exchange in the pionic channel is able to counterbalance the substantial suppression induced in OPEP when going from a cutoff mass  $\Lambda_{NN\pi}$  of  $1.3\text{GeV}$ , phenomenologically required in the (full) Bonn potential, to a value of  $1.0\text{GeV}$ . Further tensor contributions, with the same sign as pion exchange, arise from correlated  $\pi\rho$

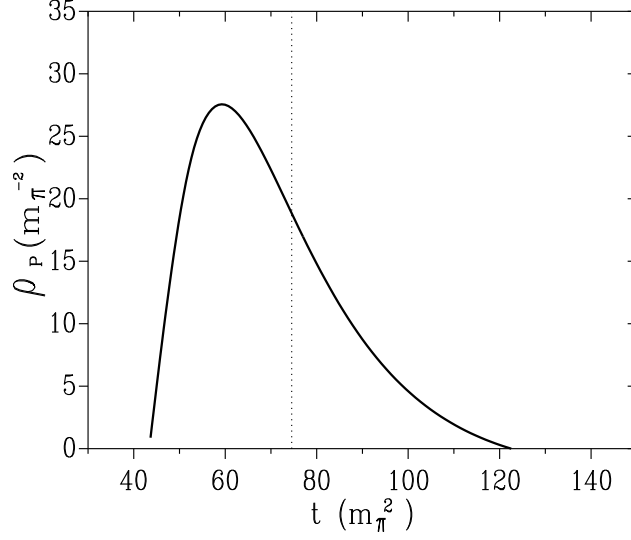


Figure 9: Spectral function  $\rho^{(\pi)}$  as a function of  $t'$  in the pseudophysical region  $t' \geq (m_\pi + m_\rho)^2$ , characterizing the correlated  $\pi\rho$  exchange contribution to the  $NN$  interaction in the pionic channel. The vertical line indicates the  $\delta$  function at  $m_{\pi'} = 1.2\text{GeV}$ , representing sharp mass  $\pi'$  exchange as used in Ref. <sup>9</sup>.

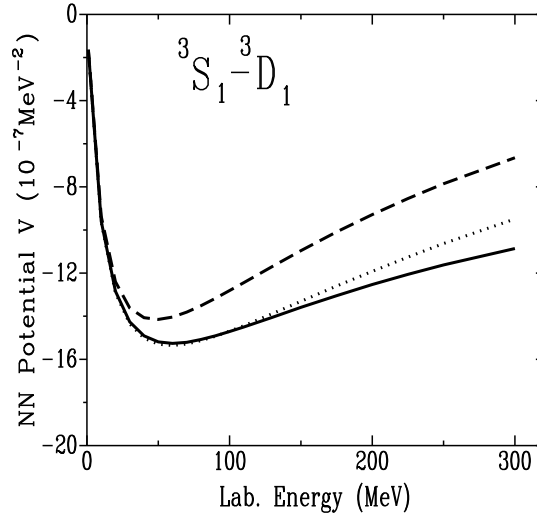


Figure 10: On-Shell  $NN$  potential  $V(q, q)$  as function of the nucleon lab. energy,  $E_{lab} = q^2/2M_N$  in the  ${}^3D_1 \rightarrow {}^3S_1$  transition. The dotted line denotes the one-pion exchange potential as used in the Bonn potential, with  $\Lambda_{\pi NN} = 1.3\text{GeV}$ . For the dashed line,  $\Lambda_{\pi NN} = 1\text{GeV}$ . The solid line results if correlated  $\pi\rho$  exchange (Fig. 6), in the pionic channel, is added to the dashed line.

exchange in the  $a_1$ -channel. If these will be included, too,  $\Lambda_{NN\pi}$  can be decreased further, into the region of  $0.8\text{GeV}$ . Thus the inclusion of correlated  $\pi\rho$  exchange in a meson exchange  $NN$  model should allow to use the correct, soft  $\pi NN$  formfactor, and thus resolve a long-standing puzzle.

## 6. Concluding remarks

In this talk, I have tried to convince you that, in low energy baryon-baryon interactions, chiral symmetry does not appear to be the dominant symmetry: A meson exchange model like the Bonn potential, which violates (to some extent) chiral symmetry, is able to describe the data quantitatively. On the other hand, a model strictly obeying chiral symmetry but restricting itself to pions as mesonic degrees of freedom and one-loop contributions shows noticeable deficiencies in the description of the empirical situation, already at very low energies. A minimal requirement for improvement would be the inclusion of two-loop contributions, i.e. to go to still higher order in the chiral expansion, in order to take at least part of the  $2\pi$ -correlation effects (“ $\sigma$ ” and  $\rho$  exchange) into account

Anyhow, there are a lot of baryonic processes whose physics is dominated by quite high orders. For example, we have recently shown<sup>21</sup> that the  $\bar{p}p \rightarrow \bar{\Sigma}\Sigma$  reaction goes predominantly through the  $\bar{\Lambda}\Lambda$  intermediate state, with strong initial ( $\bar{p}p$ ), intermediate ( $\bar{\Lambda}\Lambda$ ), and final ( $\bar{\Sigma}\Sigma$ ) state interactions. Each interaction itself has sizable higher order contributions, e.g. annihilation processes into 2 (or more) mesons. A treatment of these coupled channels effects in the chiral approach, including systematically all diagrams at the required order, is surely beyond our capabilities.

In this area of medium energy physics to be studied with our COSY accelerator, it appears more efficient not to single out the Goldstone bosons as relevant degrees of freedom but to include from the beginning higher mass mesons as mediators of baryonic interactions, in this way summing up an important class of higher order correlation effects, as done already for the  $\Delta$ -isobar in Ref. <sup>6</sup>. Further selected summations of processes to arbitrarily high order, in a potential-type coupled channel framework, have to be performed. Necessarily the full and exact implications of chiral symmetry are then lost.

Clearly, as always in physics, the actual treatment of a given theory (kind of approximations) depends on the phenomena under study and on the questions addressed. If, for example, the main issue is to study modifications of hadronic interactions in the medium, chiral symmetry gains much more importance due to chiral restoration in matter. Thus, in order to study such effects seriously, a strictly chiral model is probably required. Still, one should always be aware about what has been (necessarily?) sacrificed and about the consequences.

## References

1. see e.g. H Leutwyler, Chiral effective Lagrangians, Schladming and Boulder Lectures, Bern preprint BUTP-91/26 (1991); G. Ecker, Chiral perturbation theory, CERN preprint Th. 6660/92
2. U. G. Meissner, *Rep. Prog. Phys.* **56** (1993) 903.
3. L. S. Celenza, A. Pantziris, and C. M. Shakin, *Phys. Rev. C* **46** (1992) 2213.
4. C. A. da Rocha and M. R. Robilotta, *Phys. Rev. C* **49** (1994) 1818.
5. M. Birse, *Phys. Rev. C* **49** (1994) 2212.
6. C. Ordonez, L. Ray, and U. van Kolck, *Phys. Rev. Lett.* **72** (1994) 1982.
7. R. Machleidt, K. Holinde, Ch. Elster, *Phys. Rep.* **149** (1987) 1.
8. G. Janssen, K. Holinde, and J. Speth, *Phys. Rev. Lett.* **73** (1994) 1332.
9. K. Holinde and A. W. Thomas, *Phys. Rev. C* **42** (1990) R1195; J. Haidenbauer, K. Holinde, and A. W. Thomas, *Phys. Rev. C* **49** (1994) 2331.
10. D.V. Bugg and R.A. Bryan, *Nucl. Phys. A* **540** (1992) 449.
11. V.G.J. Stoks, R.A.M. Klomp, M.C.M. Rentmeester, and J.J. de Swart, *Phys. Rev. C* **48** (1993) 792.
12. H.-C. Kim, J. W. Durso, and K. Holinde, *Phys. Rev. C* **49** (1994) 2355.
13. T. E. O. Ericson and M. Rosa Clot, *Nucl. Phys. A* **405** (1983) 497; *Ann. Rev. Nucl. Part. Sci.* **35** (1985) 271.
14. S. A. Coon and M. D. Scadron, *Phys. Rev. C* **23** (1981) 1150; *Phys. Rev. C* **42** (1990) 2256; A. W. Thomas and K. Holinde, *Phys. Rev. Lett.* **63** (1989) 2025.
15. K. F. Liu, S. J. Dong, T. Draper, and W. Wilcox, UK/94-01 preprint, hep-lat/9406007.
16. T. Ueda, *Phys. Rev. Lett.* **68** (1992) 142.
17. G. Janssen, J. W. Durso, K. Holinde, B. C. Pearce, and J. Speth, *Phys. Rev. Lett.* **71** (1993) 1978; G. Janssen, K. Holinde, and J. Speth, *Phys. Rev. C* **49** (1994) 2763.
18. D. Lohse, J. W. Durso, K. Holinde, and J. Speth, *Nucl. Phys. A* **516** (1990) 513.
19. Particle Data Group, K. Hikase et al., *Phys. Rev. D* **45** (1992) 100.
20. J. A. Dankowych et al., *Phys. Rev. Lett.* **38** (1981) 580.
21. J. Haidenbauer, K. Holinde, and J. Speth, *Nucl. Phys. A* **562** (1993) 317.

# HADRON-HADRON INTERACTIONS \*

K. Holinde

*Institut für Kernphysik (Theorie), Forschungszentrum Jülich GmbH,  
D-52425 Jülich, Germany*

## ABSTRACT

The present status of the chiral approach to the  $NN$  interaction as proposed by Weinberg is discussed. The important role of correlation effects and explicit vector meson ( $\rho, \omega$ ) exchange in the dynamics of baryon-baryon interactions is demonstrated. As an example, the inclusion of the exchange of a correlated pair of  $\pi$  and  $\rho$  meson between two nucleons appears to be mandatory in order to resolve a long-standing puzzle concerning the formfactor at the pion-nucleon-nucleon vertex.

## 1. Introduction

Quantum chromodynamics (QCD) is the underlying theory of strong interactions, with quarks and gluons as fundamental degrees of freedom. However, in the non-perturbative region of low and medium energy physics, mesons and baryons definitely keep their importance as efficient, collective degrees of freedom for a wide range of nuclear phenomena. There is a widespread view that a successful effective field theory in terms of hadronic degrees of freedom should have the same symmetries as QCD. Chiral symmetry, in the limit of vanishing quark masses, is an exact QCD symmetry; chiral perturbation theory<sup>1</sup> is an effective field theory in terms of the light pseudoscalar mesons ( $\pi, K, \eta$ ), the Goldstone bosons of spontaneously broken chiral symmetry. It is important to realize that such an effective field theory is mathematically equivalent to QCD. At sufficiently low energies, smaller than the QCD mass scale of about 1GeV, it leads to a systematic expansion of effective Lagrangians and scattering amplitudes in powers of momenta and quark masses (the latter arise from the symmetry breaking terms).

Of course, the effectiveness (as a fastly converging scheme) of chiral perturbation theory is by definition restricted to quite low energies. Moreover, a perturbational method can only work if the interactions are weak, which is the case for reactions involving the Goldstone bosons as external particles. Given these constraints, chiral perturbation theory is remarkably successful; for a review, see e.g. the recent article by Meissner<sup>2</sup>.

---

\*Invited talk presented at the Conference on Physics with GeV-Particle Beams, Jülich, Germany, August 22-25, 1994.

On the other hand, for baryon-baryon and baryon-antibaryon interactions strong correlation effects appear already at threshold; it is hard to get such effects from an expansion which, for practical reasons, has to be limited to low orders. Furthermore, higher-mass mesons, especially vector mesons  $\rho$  and  $\omega$ , play an important role. In my opinion, a successful description requires to treat both dynamical mechanisms explicitly, as will be discussed below.

## 2. Chiral Dynamics in the nucleon-nucleon system.

Let me start by looking at present chiral treatments of the nucleon-nucleon ( $NN$ ) system. Recently, quite a lot of papers have appeared dealing with this issue <sup>3-6</sup>. Whereas Refs. <sup>3-5</sup> concentrated on the chiral structure of a specific contribution to the  $NN$  interaction, namely  $2\pi$ -exchange, Ref. <sup>6</sup> presented a “complete”  $NN$  potential strictly obeying chiral symmetry. It is based on the most general effective chiral Lagrangian involving low momentum pions, nonrelativistic nucleons and  $\Delta$ -isobars, and is considered up to third order  $((Q/M)^3$ , with  $Q$  a typical external momentum and  $M$  the QCD mass scale) in the chiral expansion, thus containing tree as well as one-loop diagrams.

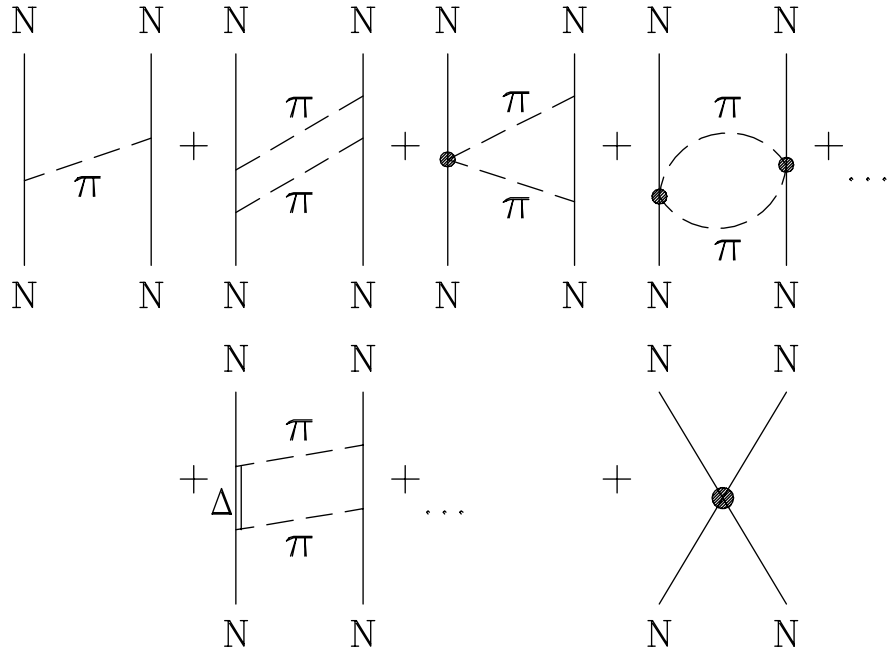


Figure 1: Diagrams included in the chiral approach of Ref. <sup>6</sup>.

In diagrammatic terms, the resulting  $NN$  potential has the structure shown in Fig. 1. It consists of one-pion-exchange (OPE) and  $2\pi$ -exchange terms with  $N$  and  $\Delta$  intermediate states. There are additional  $2\pi$ -exchange processes in the chiral approach (Ref. <sup>6</sup>) involving the  $N\bar{N}\pi\pi$  vertex (see Fig. 1), whose presence is dictated by chiral symmetry. However, due to partial cancellations (Refs. <sup>5, 4</sup>) they are

Table 1: Deuteron properties predicted by the chiral model of Ref. <sup>6</sup>, the Bonn  $NN$  potential (Ref. <sup>7</sup>), and the Bonn potential with a soft  $\pi NN$  form factor ( $\Lambda_{\pi NN} = 1GeV$ ) plus correlated  $\pi\rho$  exchange (Ref. <sup>8</sup>) as discussed in Section 5. For the experimental values, see Refs. <sup>7, 9</sup>.

	experiment	chiral model (Ref. <sup>6</sup> )	Bonn (Ref. <sup>7</sup> )	modified Bonn
Binding energy (MeV)	2.2245754	2.18	2.2247	2.2246
Quadrupole moment ( $fm^2$ )	$0.2859 \pm 0.0003$	0.231	0.2807	0.2791
asymptotic D/S ratio	$0.0256 \pm 0.0004$ ( $0.0271 \pm 0.0008$ )	0.0239	0.0267	0.0266

actually quite small, much smaller e.g. than “ $\sigma$ ”- exchange representing correlated  $2\pi$ -exchange in the scalar-isoscalar channel, which provides the main part (about  $2/3$ , see Ref. <sup>7</sup>) of the  $NN$  intermediate range attraction. The chiral approach absorbs this contribution together with other important pieces involving vector ( $\rho, \omega$ ) mesons into the contact terms, i.e. terms of zero range (last diagram of Fig. 1). In order to solve the corresponding Schroedinger equation a Gaussian cutoff function,  $exp(-Q^2/L^2)$ , with  $L = 3.9fm^{-1}$ , has been used. Results for some low ( $S$  and  $P$ )  $NN$  partial wave phase shifts are shown in Fig. 2 (taken from Ref. <sup>6</sup>), in comparison to those obtained from the (full) Bonn potential<sup>7</sup>. In addition, table 1 shows some deuteron parameters.

In this first confrontation of a chiral  $NN$  potential à la Weinberg to the very precise  $NN$  data rough agreement is reached in the low-energy domain. Note that this model has 26 parameters available (mainly the coefficients in the contact terms) compared to about 10 meson-baryon coupling constants and formfactor parameters in the Bonn potential. A combined look at the  $\varepsilon_1$ -parameter and deuteron parameters ( $Q$ ,  $D/S$ ) is instructive since both measure the size of the  $NN$  tensor force. Obviously, in the present chiral model, the energy dependence of this piece is not realistic since the deuteron values are too low whereas the  $\varepsilon_1$ -values grow too fast with increasing energy. There are two possible sources for this discrepancy: First, the chiral expansion introduces a polynomial momentum dependence, with adjustable parameters, at the  $\pi NN$  vertex; it should be checked by the authors of Ref. <sup>6</sup> whether their parametrization chosen is in reasonable agreement with the known monopole structure of the  $\pi NN$  formfactor, see Section 4. Furthermore,  $\rho$ -exchange provides an important contribution to the tensor force (see Section 3) reaching out well into intermediate  $NN$  distances of  $1 - 2fm$ . It is highly questionable whether this piece (as well as “ $\sigma$ ” and  $\omega$  exchange) can be sufficiently represented by zero-range contact terms.

In my opinion, in present chiral approaches to the  $NN$  system, the price you pay (having to treat important contributions in a very rough way) is too high for

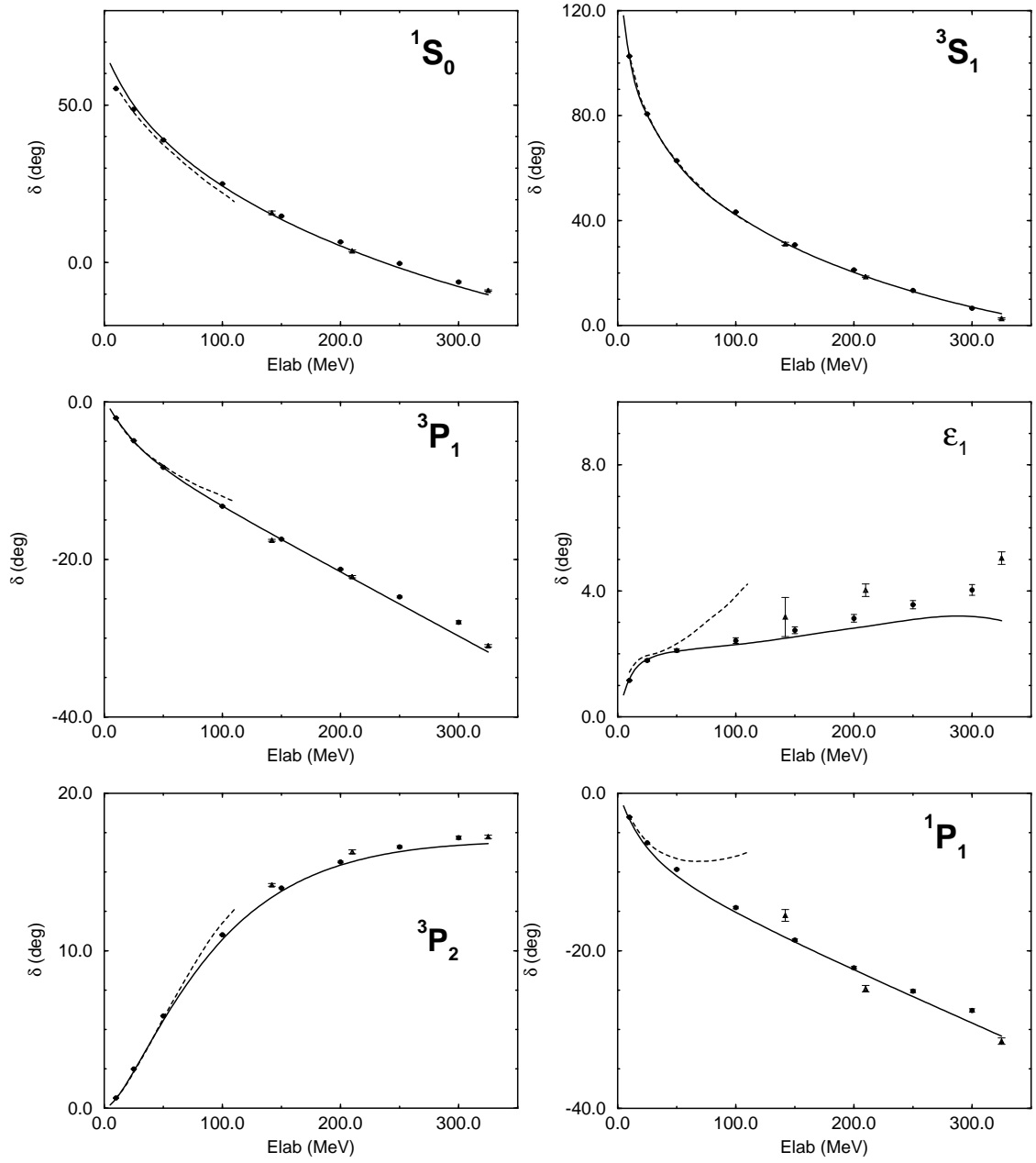


Figure 2:  $NN$  phase shifts, in selected partial waves, as a function of the nucleon lab. energy. The solid lines give the predictions derived from the Bonn potential (Ref. <sup>7</sup>) whereas the dashed lines, taken from Ref. <sup>6</sup>, originate from the chiral approach. The experimental error bars are taken from Refs. <sup>10, 11</sup>



what you get (a strict chirally symmetric  $V_{NN}$  derived from a systematic expansion).

### 3. Structure of $\pi$ and $\rho$ exchange in the $NN$ system

It is well known that the physics of “ $\sigma$ ” and  $\rho$  exchange, so important in the  $NN$  system, is mainly built up by correlated  $2\pi$ -exchange. (For a recent dynamical model suitable for the discussion of medium modifications, see the paper by Kim et al.<sup>12</sup>.) Therefore, in principle, the chiral approach can take such effects, at least to some extent, into account by going to still higher orders in the chiral expansion, at the expense of getting additional open parameters.

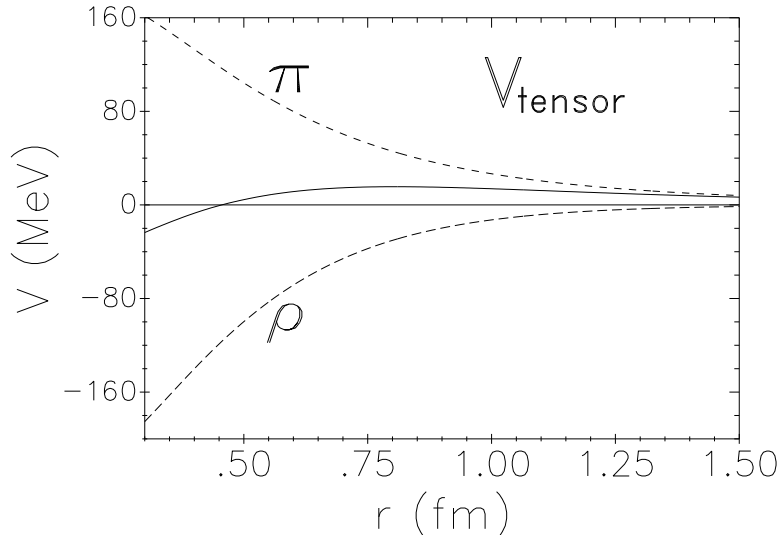


Figure 3:  $NN$  tensor force  $V_T(r)$  as function of the two-nucleon distance  $r$ , due to  $\pi$  and  $\rho$  exchange. The solid line denotes the sum of both contributions. The parameter values are taken from OBEPR (Ref. <sup>7</sup>).

The importance of  $\rho$ -exchange for the dynamics of the  $NN$  system derives from the following fact: It provides a sizable tensor force, which has opposite sign to the tensor force generated by one-pion-exchange, see Fig. 3. Thus there is a strong cancellation, over a relatively broad range of energies and distances, between  $\pi$  and  $\rho$  exchange in the tensor channel. A similar cancellation occurs in the strange sector, between  $K$  and  $K^*$  exchange, e.g. in the hyperon-nucleon interaction. Therefore, in the  $NN$  (and in the baryon-baryon system in general) it is strongly suggested to always group  $\pi$  and  $\rho$  (as well as  $K$  and  $K^*$ ) together in order to reach sufficient convergence in the expansion of the irreducible kernel (potential). To single out  $\pi$ -exchange as done in the chiral approach might be more systematic from a formal point of view; on the other hand, by putting  $\rho$ -exchange into the contact terms, one essentially loses the strong convergence-generating mechanism at intermediate distances provided by  $\rho$ -exchange. Thus, from a physical standpoint, it appears mandatory to treat  $\pi$  and  $\rho$  exchange on an equal footing.

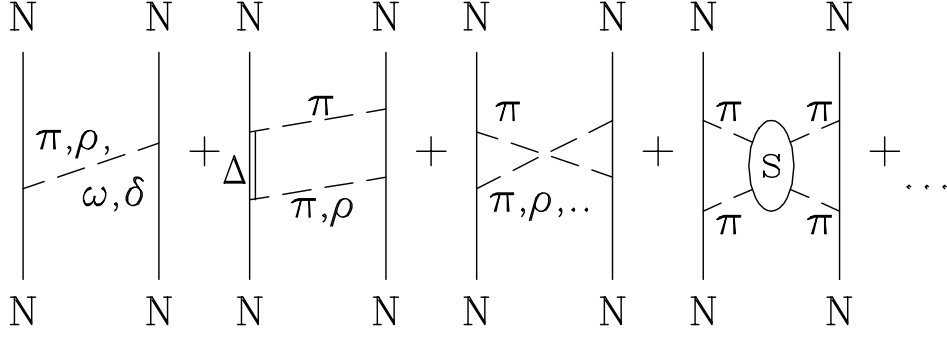


Figure 4: Diagrams included in the Bonn  $NN$  potential<sup>7</sup>.

In fact, this procedure has been an essential guideline when constructing the Bonn potential. Unfortunately (though for understandable reasons, see below) it was not followed to a sufficient degree: Whereas, in second-order diagrams (cp. Fig. 4)  $\pi\pi$  as well as  $\pi\rho$  exchange have been included for uncorrelated processes (with  $N$  and  $\Delta$  intermediate states) this has not been done for correlated processes: correlated  $2\pi$ -exchange processes have been included (in terms of sharp-mass  $\sigma'$  and  $\rho$  exchange) but correlated  $\pi\rho$  processes have been left out. The reason is quite simple: The evaluation of this missing piece is technically quite complicated, much more involved (due to the spin of the  $\rho$ ) compared to correlated  $2\pi$ -exchange. More importantly, a dynamical model for the interaction between a  $\pi$  and a  $\rho$  meson was not available.

At the time of the construction of the Bonn potential (about 10 years ago) the omission of this piece did not seem to be serious.  $NN$  scattering data in a broad energy range as well as the deuteron data are described quantitatively with the full Bonn model. So why care about a missing piece whose practical relevance was not at all obvious? Soon after the publication of the Bonn potential in 1987 it became however clear that omission of correlated  $\pi\rho$  exchange demanded a high price, and this has to do with the structure of the  $\pi NN$  vertex.

#### 4. The $\pi NN$ vertex

Basic ingredients of the Bonn meson exchange  $NN$  model<sup>7</sup> are the meson-baryon couplings or vertex functions visualized in Fig. 5. These vertex functions are the “elementary” building blocks of an effective and consistent meson exchange description based on QCD.

The analytic structure of these couplings is (essentially) determined by the quantum numbers of the particles involved at the vertex. The strength is parametrized by coupling constants  $g_{B'B\alpha}$ ; in addition, formfactors with cutoff masses  $\Lambda_{B'B\alpha}$  as additional parameters are included, which parametrize the effect of the hadron extension and therefore represent a truly physical concept. In general, the formfactor depends on all four-momenta of the particles involved at the vertex, i.e.  $F_{B'B\alpha} = F(q_{B'}^2, q_B^2, q_\alpha^2)$

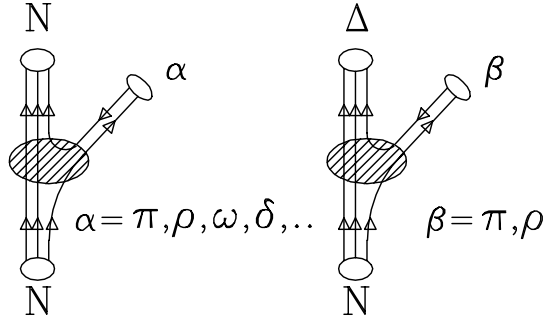


Figure 5: Baryon-baryon-meson couplings included in the Bonn  $NN$  potential (Ref. <sup>7</sup>).

and is normalized to 1 when all particles are on the mass shell.

While ultimately these formfactors have to be derived from QCD they are for the moment parametrized, usually in monopole form, keeping the dependence on the momentum of the exchanged particle only. With the additional suppression of the dependence on  $q_\alpha^0$ , the formfactors relevant in the  $NN$  system can then be written as

$$F_{B'B\alpha} = \frac{\Lambda_{B'B\alpha}^2 - m_\alpha^2}{\Lambda_{B'B\alpha}^2 + \vec{q}_\alpha^2} . \quad (1)$$

The cutoff masses  $\Lambda_{B'B\alpha}$  together with the coupling constants  $g_{B'B\alpha}$  represent the only parameters in the Bonn potential; they have been adjusted to the  $NN$  data. For the  $\pi NN$  cutoff mass,  $\Lambda_{NN\pi}$ , the resulting value turned out to be rather large ( $= 1.3GeV$ ) leading to a mild suppression of OPEP in the inner region ( $r \leq 1fm$ ) only, and thus to a hard formfactor. This is necessary in order to have sufficiently strong tensor force to reproduce the deuteron properties, especially the asymptotic  $D$ - to  $S$ -wave ratio and the quadrupole moment<sup>13</sup>.

However, there is a long-standing discrepancy between this rather large value required in present-day potential models and information from other sources; the latter consistently point to a much smaller value for  $\Lambda_{NN\pi}$  around  $0.8GeV$ <sup>14</sup>. In fact, a recent lattice calculation<sup>15</sup> of the  $\pi NN$  formfactor confirms this result, finding a monopole mass of  $(0.75 \pm 0.14)GeV$ . Such a soft formfactor leads to a strong suppression of the OPE tensor force already at intermediate distances, in apparent disagreement with the deuteron data. It is sometimes argued that a reduction (or even elimination) of  $\rho$  exchange in  $NN$  models would remedy the situation easily since the tensor force of  $\rho$  exchange has opposite sign compared to  $\pi$ -exchange. This can certainly be done if one looks at the deuteron channel only. However the sizable strength of  $\rho$  exchange is tightly constrained by informations from  $\pi N$  scattering via dispersion theory (see Ref. <sup>12</sup>) and in fact required by the precisely measured triplet  $P$ -wave  $NN$  phase shifts; it therefore cannot be arbitrarily changed.

Consequently we have to find mechanisms so far not included in meson exchange  $NN$  models which provide additional (short ranged) tensor force. Two years

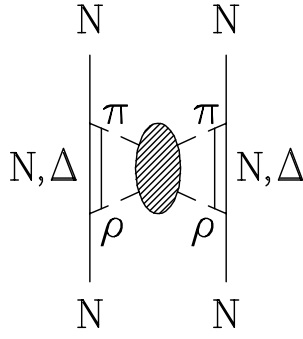


Figure 6: Model for the correlated  $\pi\rho$  exchange as evaluated in Ref. <sup>8</sup>.

ago it was pointed out by Ueda<sup>16</sup> that the contribution arising from the exchange of a correlated three-pion state between the nucleons, with the quantum numbers of a pion, should enhance the short-range tensor part of the  $NN$  interaction. Correlated  $\pi\rho$  exchange addressed in the foregoing chapter is a good part of it, and there is obviously no way around this contribution.

### 5. Correlated $\pi\rho$ exchange in the $NN$ system

The explicit evaluation of the diagram in figure 6 requires as input a realistic  $\pi\rho$   $T$ -matrix. In the absence of elastic  $\pi\rho$  scattering data (due to the fast decay of the  $\rho$  meson into 2 pions) we have to rely completely on a dynamical model.

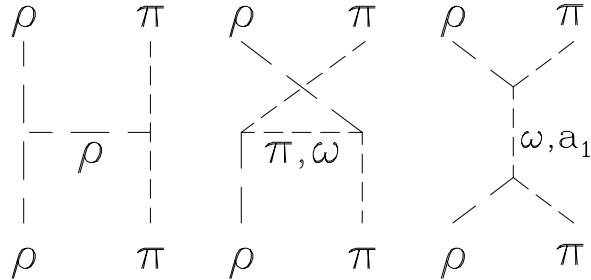


Figure 7: Driving terms for the  $\pi\rho$  interaction model of Refs. <sup>8, 17</sup>.

We<sup>17</sup> have recently constructed a corresponding potential model, in complete analogy to the  $\pi\pi$  case (Ref. <sup>18</sup>), with driving terms shown in Fig. 7. Open parameters are adjusted mainly to empirical information in the  $a_1$ -channel (the  $a_1$  decaying into  $\pi$  and  $\rho$ ), namely the resonance parameters (pole position) of the  $a_1$ -particle<sup>19</sup> ( $m_{a_1} = 1.26\text{GeV}$ ,  $\Gamma_{a_1} = 0.4\text{GeV}$ ) obtained from  $\tau$ -meson decay, and the mass spectrum obtained from charge exchange production<sup>20</sup>,  $\pi p \rightarrow 3\pi n$ , see Fig. 8. Note that the shift of the maximum of the mass spectrum away from the true pole position is due to the sizable non-pole amplitude  $T_{np}$ , obtained by iterating  $V_{np}$  (the first two diagrams of Fig. 7.).

This non-pole contribution now acts in all other channels, e.g. in the pionic channel of interest here, with a definite strength distribution, which is characteristic of the underlying model.

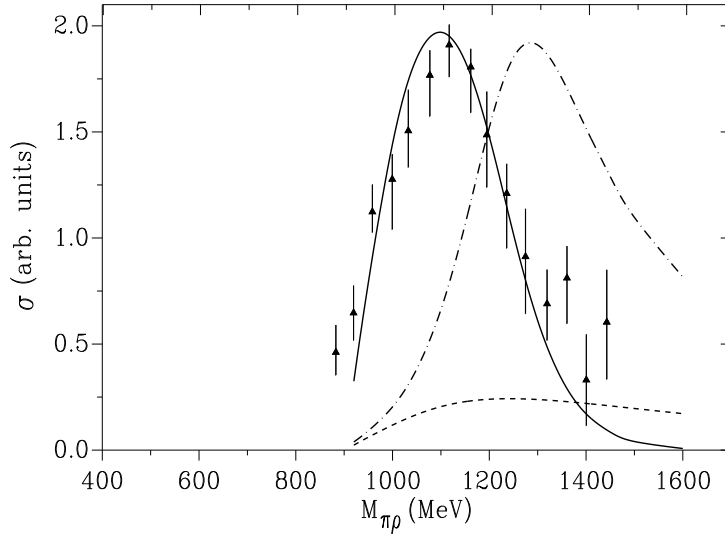


Figure 8: Mass spectrum in the  $a_1$  channel obtained from  $\pi p \rightarrow 3\pi n$  (Ref. <sup>20</sup>). The solid line shows the prediction of our full model whereas the dashed line denotes the result of the non-pole part of the  $T$ -matrix,  $T_{np}$ , only. The dash-dotted line provides the result of the pole part  $T_p$  only, with readjustment of the parameters to keep the same pole values

This  $\pi\rho$   $T$ -matrix is now inserted into the correlated  $\pi\rho$  exchange diagram of Fig. 6. The evaluation<sup>8</sup> proceeds via the same dispersion-theoretic treatment as used for the  $\pi\pi$  case in Ref. <sup>12</sup>. The result can be represented as integral over various spectral functions, the number of which depend on the considered channel. For the pionic channel we have one spectral function  $\rho^{(\pi)}$ :

$$V_{\pi\rho}^{(\pi)} \sim \int_{(m_\pi+m_\rho)^2}^{\infty} \frac{\rho^{(\pi)}(t')}{t' - t} dt'. \quad (2)$$

$\rho^{(\pi)}$  is shown in Fig. 9. Obviously the correlated part provides a sizable contribution, with a peak around  $1.1\text{GeV}$ , somewhat smaller than the mass ( $1.2\text{GeV}$ ) of the phenomenological  $\pi'$  introduced in some recent  $NN$  models to accommodate a soft  $\pi NN$  formfactor<sup>9</sup>.

Indeed, as shown in Fig. 10 and Table 1, the resulting interaction due to correlated  $\pi\rho$  exchange in the pionic channel is able to counterbalance the substantial suppression induced in OPEP when going from a cutoff mass  $\Lambda_{NN\pi}$  of  $1.3\text{GeV}$ , phenomenologically required in the (full) Bonn potential, to a value of  $1.0\text{GeV}$ . Further tensor contributions, with the same sign as pion exchange, arise from correlated  $\pi\rho$

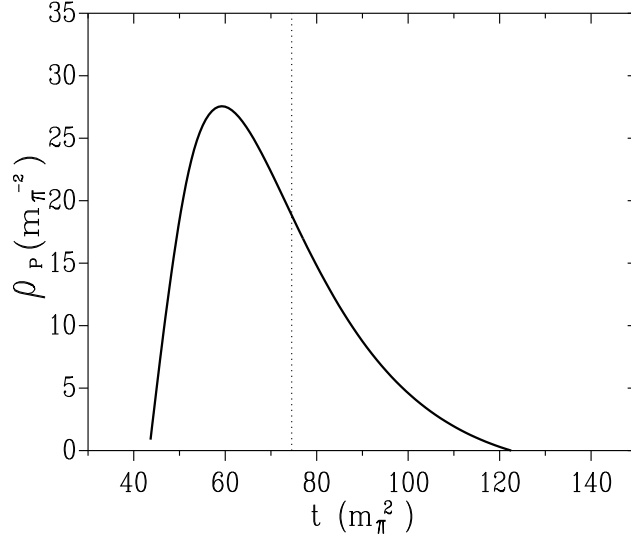


Figure 9: Spectral function  $\rho^{(\pi)}$  as a function of  $t'$  in the pseudophysical region  $t' \geq (m_\pi + m_\rho)^2$ , characterizing the correlated  $\pi\rho$  exchange contribution to the  $NN$  interaction in the pionic channel. The vertical line indicates the  $\delta$  function at  $m_{\pi'} = 1.2 GeV$ , representing sharp mass  $\pi'$  exchange as used in Ref. <sup>9</sup>.

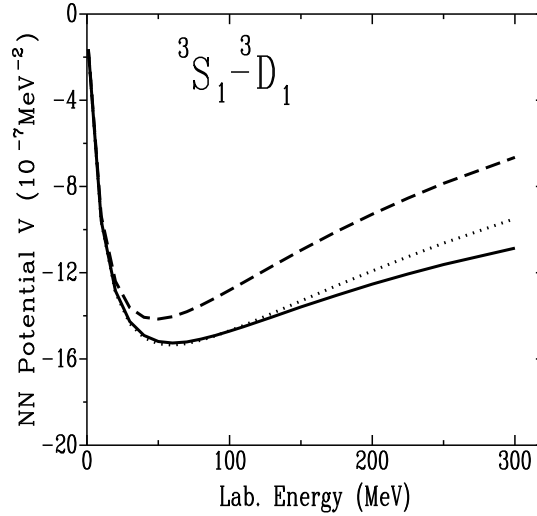


Figure 10: On-Shell  $NN$  potential  $V(q, q)$  as function of the nucleon lab. energy,  $E_{lab} = q^2/2M_N$  in the  $^3D_1 \rightarrow ^3S_1$  transition. The dotted line denotes the one-pion exchange potential as used in the Bonn potential, with  $\Lambda_{\pi NN} = 1.3 GeV$ . For the dashed line,  $\Lambda_{\pi NN} = 1 GeV$ . The solid line results if correlated  $\pi\rho$  exchange (Fig. 6), in the pionic channel, is added to the dashed line.

exchange in the  $a_1$ -channel. If these will be included, too,  $\Lambda_{NN\pi}$  can be decreased further, into the region of  $0.8\text{GeV}$ . Thus the inclusion of correlated  $\pi\rho$  exchange in a meson exchange  $NN$  model should allow to use the correct, soft  $\pi NN$  formfactor, and thus resolve a long-standing puzzle.

## 6. Concluding remarks

In this talk, I have tried to convince you that, in low energy baryon-baryon interactions, chiral symmetry does not appear to be the dominant symmetry: A meson exchange model like the Bonn potential, which violates (to some extent) chiral symmetry, is able to describe the data quantitatively. On the other hand, a model strictly obeying chiral symmetry but restricting itself to pions as mesonic degrees of freedom and one-loop contributions shows noticeable deficiencies in the description of the empirical situation, already at very low energies. A minimal requirement for improvement would be the inclusion of two-loop contributions, i.e. to go to still higher order in the chiral expansion, in order to take at least part of the  $2\pi$ -correlation effects (“ $\sigma$ ” and  $\rho$  exchange) into account

Anyhow, there are a lot of baryonic processes whose physics is dominated by quite high orders. For example, we have recently shown<sup>21</sup> that the  $\bar{p}p \rightarrow \bar{\Sigma}\Sigma$  reaction goes predominantly through the  $\bar{\Lambda}\Lambda$  intermediate state, with strong initial ( $\bar{p}p$ ), intermediate ( $\bar{\Lambda}\Lambda$ ), and final ( $\bar{\Sigma}\Sigma$ ) state interactions. Each interaction itself has sizable higher order contributions, e.g. annihilation processes into 2 (or more) mesons. A treatment of these coupled channels effects in the chiral approach, including systematically all diagrams at the required order, is surely beyond our capabilities.

In this area of medium energy physics to be studied with our COSY accelerator, it appears more efficient not to single out the Goldstone bosons as relevant degrees of freedom but to include from the beginning higher mass mesons as mediators of baryonic interactions, in this way summing up an important class of higher order correlation effects, as done already for the  $\Delta$ -isobar in Ref. <sup>6</sup>. Further selected summations of processes to arbitrarily high order, in a potential-type coupled channel framework, have to be performed. Necessarily the full and exact implications of chiral symmetry are then lost.

Clearly, as always in physics, the actual treatment of a given theory (kind of approximations) depends on the phenomena under study and on the questions addressed. If, for example, the main issue is to study modifications of hadronic interactions in the medium, chiral symmetry gains much more importance due to chiral restoration in matter. Thus, in order to study such effects seriously, a strictly chiral model is probably required. Still, one should always be aware about what has been (necessarily?) sacrificed and about the consequences.

## References

1. see e.g. H Leutwyler, Chiral effective Lagrangians, Schladming and Boulder Lectures, Bern preprint BUTP-91/26 (1991); G. Ecker, Chiral perturbation theory, CERN preprint Th. 6660/92
2. U. G. Meissner, *Rep. Prog. Phys.* **56** (1993) 903.
3. L. S. Celenza, A. Pantziris, and C. M. Shakin, *Phys. Rev. C* **46** (1992) 2213.
4. C. A. da Rocha and M. R. Robilotta, *Phys. Rev. C* **49** (1994) 1818.
5. M. Birse, *Phys. Rev. C* **49** (1994) 2212.
6. C. Ordóñez, L. Ray, and U. van Kolck, *Phys. Rev. Lett.* **72** (1994) 1982.
7. R. Machleidt, K. Holinde, Ch. Elster, *Phys. Rep.* **149** (1987) 1.
8. G. Janssen, K. Holinde, and J. Speth, *Phys. Rev. Lett.* (), in print.
9. K. Holinde and A. W. Thomas, *Phys. Rev. C* **42** (1990) R1195; J. Haidenbauer, K. Holinde, and A. W. Thomas, *Phys. Rev. C* **49** (1994) 2331.
10. D. V. Bugg and R. A. Bryan, *Nucl. Phys. A* **540** (1992) 449.
11. V. G. J. Stoks, R. A. M. Klomp, M. C. M. Rentmeester, and J. J. de Swart, *Phys. Rev. C* **48** (1993) 792.
12. H.-C. Kim, J. W. Durso, and K. Holinde, *Phys. Rev. C* **49** (1994) 2355.
13. T. E. O. Ericson and M. Rosa Clot, *Nucl. Phys. A* **405** (1983) 497; *Ann. Rev. Nucl. Part. Sci.* **35** (1985) 271.
14. S. A. Coon and M. D. Scadron, *Phys. Rev. C* **23** (1981) 1150; *Phys. Rev. C* **42** (1990) 2256; A. W. Thomas and K. Holinde, *Phys. Rev. Lett.* **63** (1989) 2025.
15. K. F. Liu, S. J. Dong, T. Draper, and W. Wilcox, UK/94-01 preprint, hep-lat/9406007.
16. T. Ueda, *Phys. Rev. Lett.* **68** (1992) 142.
17. G. Janssen, J. W. Durso, K. Holinde, B. C. Pearce, and J. Speth, *Phys. Rev. Lett.* **71** (1993) 1978; G. Janssen, K. Holinde, and J. Speth, *Phys. Rev. C* **49** (1994) 2763.
18. D. Lohse, J. W. Durso, K. Holinde, and J. Speth, *Nucl. Phys. A* **516** (1990) 513.
19. Particle Data Group, K. Hikase et al., *Phys. Rev. D* **45** (1992) 100.
20. J. A. Dankowych et al., *Phys. Rev. Lett.* **38** (1981) 580.
21. J. Haidenbauer, K. Holinde, and J. Speth, *Nucl. Phys. A* **562** (1993) 317.